Break-junction experiments on the zero-bias anomaly of non-magnetic and ferromagnetically ordered metals

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Abstract

We have investigated break junctions of normal non-magnetic metals as well as ferromagnets at low temperatures. The point contacts with radii $0.15 − 15\,\mathrm{nm}$ showed zero-bias anomalies which can be attributed to Kondo scattering at a single Kondo impurity at the contact or to the switching of a single conducting channel. The Kondo temperatures derived from the width of the anomalies varied between 10 and $1000\,\mathrm{K}$. These results agree well with literature data on atomic-size contacts of the ferromagnets as well as with spear-anvil type contacts on a wide variety of metals.

I.   INTRODUCTION

The recent discovery of the Kondo effect in atomic-size contacts of the ferromagnets Co, Fe, and Ni demonstrates how material properties can be changed by reducing the size of the sample. In that specific case magnetic order was quenched at the junction, enabling the Kondo effect to take place [1]. Kondo scattering also seems to be behind the so-called zero-bias anomalies of point contacts of a wide variety of metals including magnets, nonmagnets, and even superconductors [2]. The latter experiments revealed a systematic variation of the zero-bias anomalies as function of contact size. However, spear-anvil type contacts usually involve interfaces which can be degraded by oxidation or a residual H_2O film, which is avoided by using mechanically controllable break junctions. Here we report break junction experiments on the ferromagnet Fe and compare them to those of non-magnetic Cu. Similar results were obtained for Co, Ni, Al, and Cd.

The resistance $R(T) \approx 2R_K/(ak_F)^2 + \rho(T)/(2a)$ of a point contact between two identical normal metals depends on the Fermi wave number k_F, the contact radius a, and the temperature-dependent specific resistivity $\rho(T)$ [3]. Here $R_K = h/e^2$. In the ballistic limit electrons cross the contact region on straight trajectories and the first term dominates. The second term provides corrections due to electron scattering in the contact region, the so-called backscattering. According to the Drude-Sommerfeld theory [4] the product of electrical resistivity and electron mean free path $\rho \cdot l = (3\pi R_K)/(2k_F^2)$ is a constant. Therefore the temperature dependence of the contact resistance can be replaced by the energy or bias-voltage dependence at low temperature

$$\frac{dV}{dI} \approx \frac{2R_K}{(ak_F)^2} \left(1 + \frac{a}{l(eV)} \right) \tag{1}$$

to extract $l(eV)$. Independent scattering processes can be separated if their respective mean free paths have different energy dependencies. This is the case for electron-phonon scattering, which sets in at energies above $5-10\,\mathrm{meV}$, and Kondo scattering at magnetic impurities that is efficient only at small energies. A Kondo impurity polarizes the surrounding electrons, forming a $\xi_K \approx \hbar v_F/k_B T_K$ large polarization cloud. Here v_F is the Fermi velocity. The electrical resistivity [5]

$$\Delta\rho(T) = \frac{\Delta\rho_0}{2} \left[1 - \frac{\ln\left(T/T_K\right)}{\sqrt{\ln^2\left(T/T_K\right) + S(S+1)\pi^2}} \right] \tag{2}$$
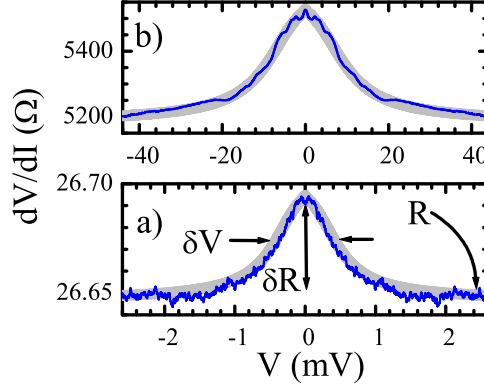
FIG. 1: Differential resistance of two typical Fe contacts at $1\,$K. Note the different scales. The spectra have been symmetrized. The thick grey lines are fits using Equation 2 with $S = 0.1$. The lower Figure shows definitions for the contact resistance R, the magnitude δR, and the width δV of the zero-bias anomaly.

due to scattering of electrons at Kondo impurities depends on the Kondo temperature T_K and the effective spin S. It reaches a maximum (in the unitary limit) of $\Delta\rho_0 = c \cdot 2R_K/k_F$ at low temperatures proportional to the impurity concentration c (impurities per conduction electron). Even a single magnetic impurity can change dramatically the resistance of a point contact.

II. EXPERIMENTAL AND RESULTS

We investigated mechanically-controllable break junctions at $1\,$K in vacuum. Lower temperatures down to $0.1\,$K or higher ones up to $4.2\,$K did not affect the results. Cu is a non-magnetic normal metal and Fe a band-ferromagnet with $T_{Curie} = 1043\,$K [4]. The samples were made of wires with $0.1 - 0.5\,$mm diameter. The wire was glued onto a flexible bending plate and a groove was cut into the wire with a sharp knife, abrasive paper, or a thin corundum blade to define the break position. After installation the radii of the unbroken contacts were about $5\,\mu$m. They had residual resistance ratios of approximately 25, thus contacts down to about $1\,\Omega$ should be in the ballistic limit. Figure 1 shows the spectra of a) a low-resistance and b) a high-resistance Fe contact together with th definition of the various parameters.

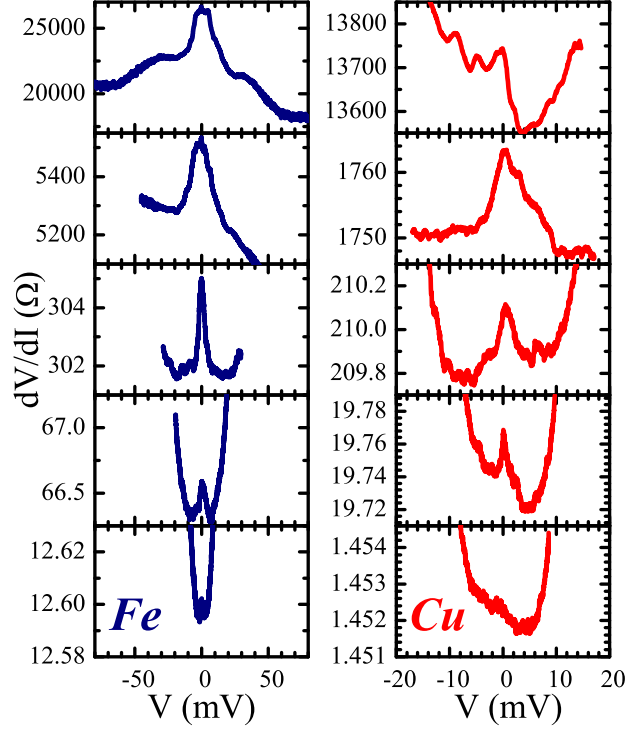Figure 2 displays two series of typical spectra of Fe and Cu contacts. Low-resistance

FIG. 2: Typical $dV/dI(V)$ spectra of Fe and Cu break junctions at $1\,\mathrm{K}$. To obtain the magnitude δR and width δV of the zero-bias anomaly the spectra were usually symmetrized first.

contacts usually showed the zero-bias anomaly, unless it was hidden in the background noise, together with the typical features of electron-phonon interaction that indicate ballistic transport. When the contact radius was reduced and the resistance increased, the relative magnitude of the zero-bias anomaly grew and, at the same time, the spectroscopic features of electron-phonon interaction became suppressed. In few cases we found an inverted zero-bias anomaly, a minimum, of comparable size as the maximum. Its origin is unclear - possibly it is caused by an accidental fabrication of a tunnel junction - and because it was only rarely observed we could not study it in detail. Very often the zero bias peaks showed multiple sub-structures, like some of the contacts in Figure 2, that looked like resonances.

Figure 3 summarizes the data. Over a wide range of contact resistances the magnitude of the zero-bias anomaly $\delta R \sim R^2$ for Fe while Cu has a systematically weaker $\delta R \sim R^{3/2}$ dependence. These dependencies contrast the typical spectroscopic features like the electron-phonon interaction which vary as $\delta R \sim \sqrt{R}$ according to Equation 1. There is no noticeable transition between small and large contacts, indicating that the tiny zero-bias anomalies at small R develop directly into the huge anomalies at large R. Thus the same mechanism
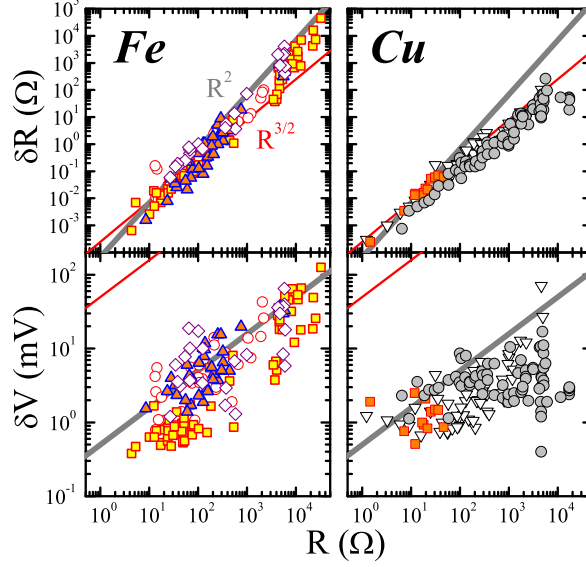
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FIG. 3: Magnitude δR as well as width δV of the zero-bias anomaly as function of resistance R of Fe and Cu break junctions at 1 K. The thick solid lines are $\delta R = (9\pi/16)R^2/R_K$ and $\delta V = 2 \cdot \hbar v_F/e\xi_K$ when the Kondo length equals $\xi_K = 100 \cdot a$ as discussed in the text. The thin solid lines indicate a smaller slope of $R \sim R^{3/2}$ and a Kondo length $\xi_K = a$. Different symbols indicate different series of measurements.

is responsible for those anomalies, independent of the contact size. Within the scattering of data points in Figure 3, one can also recognize a trend towards larger widths when the resistance increases.

III. DISCUSSION

A single impurity in the unitary limit contributes $\delta R = (9\pi R^2)/(16R_K)$ to the magnitude of the zero-bias anomaly [2] - the same as switching of a single conducting channel. This describes the experimental data for Fe in Figure 3 quite well. The width of the anomalies varies between $1\,\mathrm{mV}$ for large contacts and $100\,\mathrm{mV}$ for small contacts, implying Kondo lengths between $1\,\mu\mathrm{m}$ and $10\,\mathrm{nm}$. This is about 100 times larger than the contact radius and supports the idea that a single impurity is responsible for the anomalies [2].

Kondo phenomena in small-scale devices have been observed, for example, for tunneling into a single magnetic atom on a metallic surface [6] or in quantum-point contacts and quantum dots in a two-dimensional electron gas, where a single electron sits either in the

dot [7–10] or in a shallow potential minimum near the center of the point contact [11]. Transport through the constriction depends then on the spin of this single electron. We have suggested a similar picture that one or few electrons are trapped near the contact and polarize the conduction electrons in the contact region [2]. Another scenario has been suggested recently for atomic-size contacts of the ferromagnets Fe, Co, and Ni that had only few conducting channels and resistances near R_K. There the zero-bias anomalies were attributed to the Kondo effect caused by the changed band structure at the contact [1]. Whether this could play a role in our experiments is unclear.

IV.   CONCLUSIONS

We have found a reproducible dependence of the magnitude of the zero-bias anomalies as function of contact size for Fe as well as for Cu. If we accept that the Kondo effect is possible at atomic-size Fe contacts because ferromagnetism is quenched by the small size, it should also be possible in junctions of Cu which is *per se* non-magnetic. Making the contacts larger does not suppress the Kondo effect, as it survives at least till the radii become larger than about 15 nm.

V.   ACKNOWLEDGEMENTS

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